David and Lucile Packard Foundation
Grant #2008-32689 April 2010

A spatial analysis of greenhouse gas emissions from agricultural fertilizer usage in the US

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WINROCK
INTERNATIONAL

EXECUTIVE SUMMARY

Changing farming practices is one of the most effective ways to reduce emissions of gases with high global warming potential into the atmosphere. In particular, improved farming practices can play a critical role in addressing nitrous oxide emissions, as agricultural use of nitrogen fertilizer constitutes the main source of this potent greenhouse gas. Therefore, adjustments to farm practices are among the most cost-effective ways to reduce emissions of large amounts of N_2O into the atmosphere, a gas that is 310 times more potent for global warming than CO_2.

The objective of this analysis is to estimate average annual nitrous oxide emissions from three major crops grown in the United States - corn, cotton, and wheat. In total, 2,454 counties in 31 states where the three crops are grown are analyzed here (Figure A1). In total, the area of the three crops was 129 million acres with 55% wheat, 40% corn and 7% cotton.

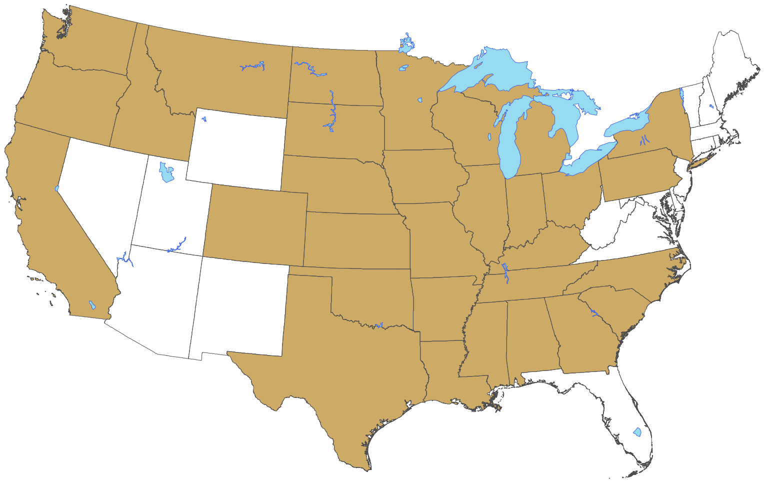

Figure A1. States in the analysis.

In terms of fertilizer, an estimated annual total of 6.2 million tons of nitrogen is added to the 129 million acres of wheat, corn and cotton. Seventy-one percent of the total fertilizer addition is to corn with 23% to wheat and 6% to cotton.

The basis of the direct and indirect emission calculations is a detailed empirical model that is discussed in the companion report to this work (hereafter referred to as the modified Bouwman model—MBM). The MBM incorporates various factors including quantity of fertilizer used, type of fertilizer, soil texture and drainage, pH and soil carbon concentration to predict nitrous oxide emissions. The companion report shows that the approach of the MBM is not sufficient at the project level, however, for a broad national analysis the approach is ideal. Inputs for this model included fertilzer type, fertilzer amount, soil properties such as pH, organic carbon, texture and drainage ability. The model was run three times for three different fertilizer types, anhydrous ammonia (AA), urea or urine (U), and urea-ammonium nitrate (UAN) often refered to as liquid nitrogen.

Our analysis resulted in an estimate of total annual N2O emission of **61 million tons of carbon dioxide equivalent** for the three crops across the 31 states. Seventy percent of these emissions were from corn fields, 25% from wheat fields and 5% from cotton.

Per acre nitrous oxide emissions ranged between 0.12 and 1.45 t CO_2-e annually and this varied among the fertilizer types. Geographically, high emissions were located in Illinois moving northwest through Iowa and western Minnesota into North Dakota. This combined area has the highest emissions and the most contiguous area of high emissions in the nation (Figure A2). Coastal areas of the eastern USA also show tendency to relatively high emissions. Emissions from corn farms were higher than emissions from either cotton or wheat (Figure A3).

Iowa leads all states in total emissions despite only growing one crop included in the analysis, corn. States that grow a combination of corn and wheat showed high emission values as well. Cotton states were the lowest in total emissions, having both the least area and the least annual emission value per acre (Figure A4).

The analysis highlights the scale and spatial variation in nitrous oxide emissions from corn, wheat and cotton croplands in the US. A potential outcome could be a targeting of emission reduction interventions, especially in the high emitting states, to maximize the reduction in atmospheric greenhouse gas emissions.

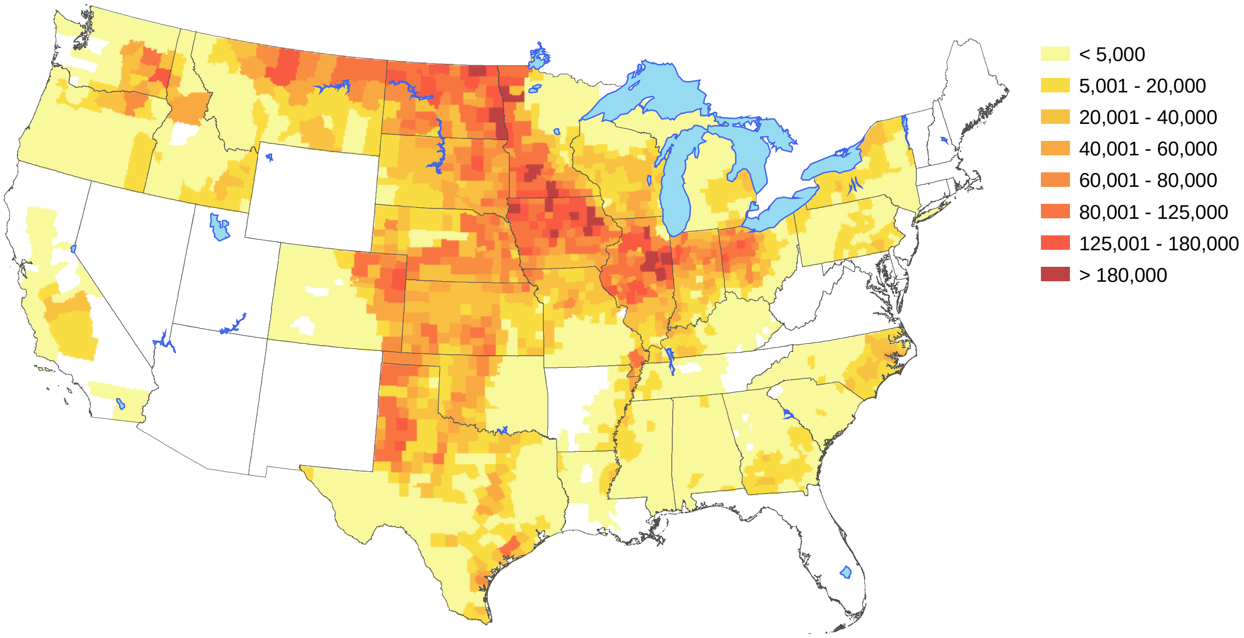

Figure A2. Estimated total county-level annual emissions from corn, wheat and cotton for anhydrous ammonia fertilizer in t CO$_2$-e

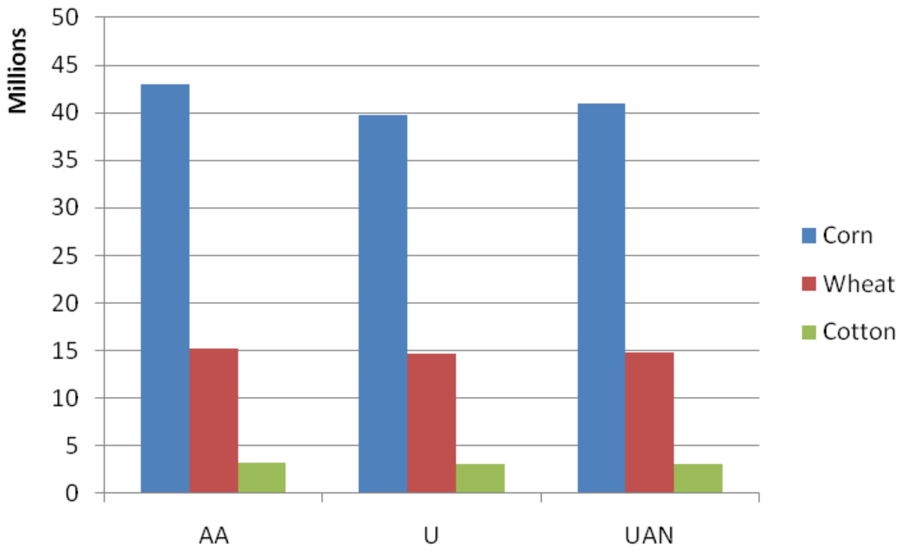

Figure A3. Estimated total annual emissions from corn, wheat and cotton from 31 states for three fertilizer types, in t CO_2-e.

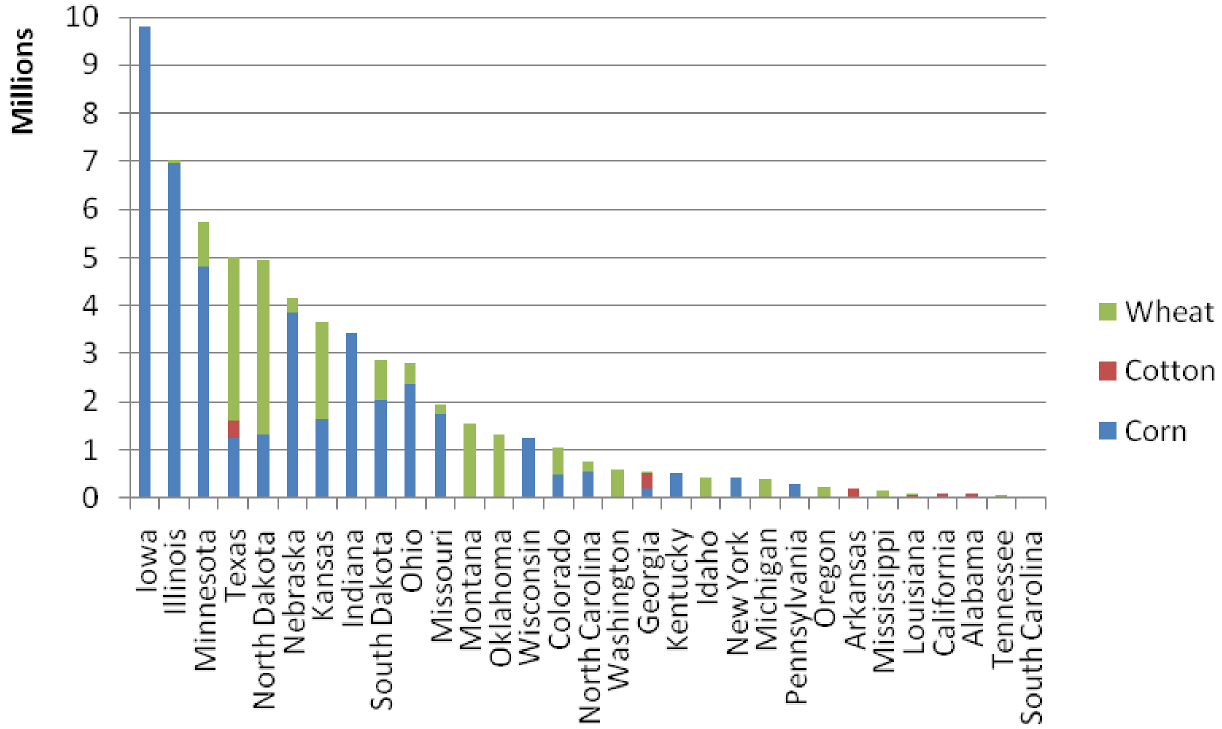

Figure A4. Contribution of each crop to each state's total annual emissions using anhydrous ammonia fertilizer (commonly used and cheapest to use), in t CO_2-e.

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ACKNOWLEDGEMENTS

Cite as:

Pearson, TRH, Grimland, S, and Brown, S. 2010. A spatial analysis of greenhouse gas emissions from agricultural fertilizer usage in the US. Report to Packard Foundation under #2008-32689

LIST OF FIGURES AND TABLES

1.0 INTRODUCTION

Changing farming practices is one of the most effective ways to reduce emissions of gases with high global warming potential into the atmosphere. In particular, improved farming practices can play a critical role in addressing nitrous oxide (N_2O) emissions, as agricultural use of nitrogen fertilizer constitutes the main source of this potent greenhouse gas. Therefore, adjustments to farm practices are among the most cost-effective ways to reduce emissions of large amounts of N_2O into the atmosphere, a gas that is 310 times more potent for global warming than CO_2.

In 2008 nitrous oxide from agricultural soil management was estimated to be responsible for 3.6% of net US emissions (EPA 2010). Direct emissions from synthetic fertilizer use were equal to 44.8 million t CO_2-e; indirect emissions added an additional 44.7 million t CO_2-e. The total emissions resulting from fertilizer use on US croplands was therefore 89.5 million t CO_2-e in 2008 or 1.5% of net US emissions.

Nitrous oxide is produced naturally in soils through the processes of nitrification and denitrification. Nitrification is the aerobic microbial oxidation of ammonium to nitrate, and denitrification is the anaerobic microbial reduction of nitrate to nitrogen gas (N_2). Nitrous oxide is a gaseous intermediate in the reaction sequence of denitrification and a by-product of nitrification that enters the soil and ultimately into the atmosphere. One of the main controlling factors in this reaction is the availability of inorganic N in the soil.

Excessive use of nitrogen fertilizer in agricultural systems not only contributes to greenhouse gas emissions but also impairs water quality, reduces biodiversity and threatens human health. However, in order to confront and abate the emissions of nitrous oxide we need to better understand both the magnitude and locations where emissions occur.

Simply put, nitrogen added to fields as fertilizer can have four broad destinations. It can be taken up by the plant, it can remain in the soil as an enhanced concentration of N, it can be emitted directly from the field into the atmosphere as nitrous oxide, or it can leach into the soil or run-off the top of the soil. The leached/runoff N can either continue downstream to cause pollution and/or it can be emitted into the atmosphere as nitrous oxide.

The goal of this study is to spatially estimate the quantity of nitrous oxides emissions resulting from fertilizer application from the production of three important crops in the US (wheat, corn and cotton) and to spatially represent the results to readily identify locations of high emissions by crop type. The first report of this study (Pearson and Brown 2010) showed that the Intergovernmental Panel on Climate Change (IPCC)'s Tier 1 approach is far from sufficient as it simply multiplies the quantity applied by defaults to calculate emissions. However, the first report showed that our modification of the empirically-based Bouwman et al (2002) model (MBM) is an improvement over the IPCC method, because it enables effects of differences in climate, crop management, and soil properties to be included.

2.0 PROPOSED STUDY APPROACH

2.1 Nitrous oxide calculation

The objective of this analysis is to estimate average annual emissions across the US from three important crops: wheat, corn and cotton. The analysis identifies the states/counties growing the crops, evaluates the factors that contribute to nitrogen emission, and estimate an annual emission value.

The basis of the emission calculations is the model of Bouwman et al (2002) and the allied indirect emissions calculation method that is discussed in the companion report (Pearson and Brown 2010). This model is referred to here as the modified Bouwmann model –MBM. The MBM incorporates various factors including quantity of fertilizer used, type of fertilizer, soil texture and drainage, pH and soil carbon concentration to predict nitrous oxide emissions. Pearson and Brown (2010) focused on assessing methods for accounting nitrous oxide emissions at the project level. The report shows that the approach of Bouwman et al (2002) is not sufficient at the project level, however, for a broad national analysis the approach is superior to the IPCC method. For the national analysis, we use average climatic conditions rather than the actual rainfall and temperature occuring during a specific growing season for a project scale analysis. In ournational analysis, we also use average fertilizer management techniques rather than the detailed precision that would be required on a project level.

2.2 Spatial analysis

This analysis focused on three major crops grown in the United States that use copious quantities of nitrogen fertilizer: corn, cotton, and wheat. At least one of these three crops grow in 2,454 counties in 31 states and are included in our analysis (Figure 1, Table 1).

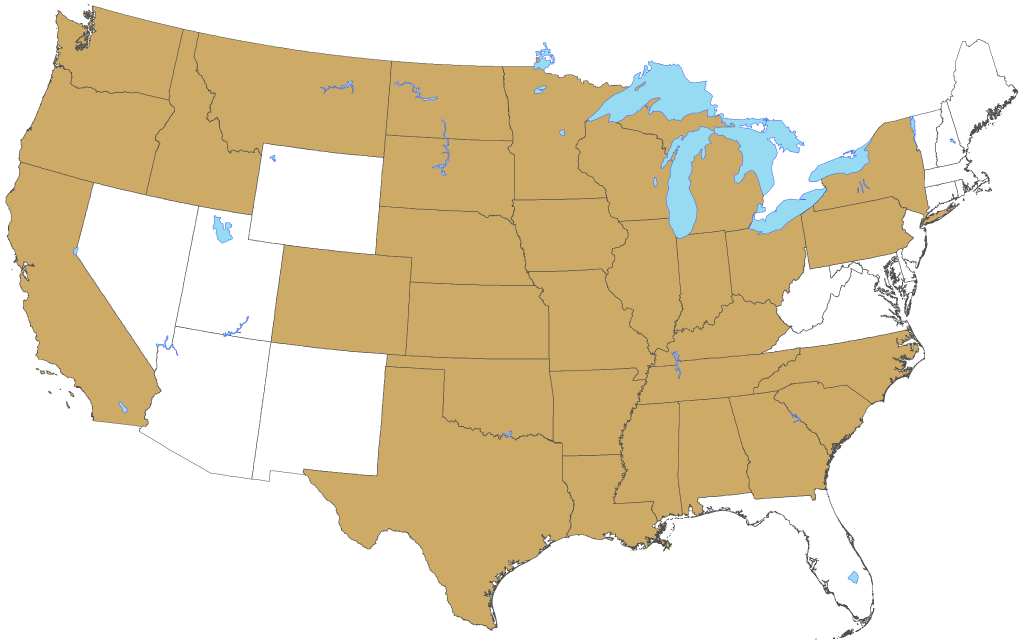


Figure 1. States that grow at least one of the three crop included in the analysis.

Table 1. States in the analysis, with area of each crop in 2009 (from the USDA, NASS Cropland Data Layer).

Corn

STATE	ACRES
Iowa	12,522,638
Illinois	11,126,533
Nebraska	8,561,006
Minnesota	6,746,774
Indiana	5,064,288
South Dakota	4,466,561
Kansas	3,758,622
Wisconsin	3,406,333
Missouri	2,765,287
Ohio	2,739,173
Texas	2,381,378
North Dakota	2,033,928
New York	1,321,142
Colorado	1,057,354
Pennsylvania	966,934
Kentucky	945,890
North Carolina	940,710
Georgia	382,628

Cotton

STATE	ACRES
Texas	5,439,387
Georgia	942,840
Arkansas	450,733
North Carolina	433,817
Mississippi	259,244
Missouri	247,921
California	237,456
Alabama	230,487
Tennessee	226,472
Louisiana	196,987
South Carolina	92,617

Wheat

STATE	ACRES
North Dakota	9,026,339
Kansas	8,521,881
Texas	6,531,585
Oklahoma	5,299,646
Montana	5,235,049
Colorado	2,615,059
South Dakota	2,584,061
Washington	2,327,074
Minnesota	1,602,884
Nebraska	1,380,301
Idaho	1,353,986
Oregon	945,590
Michigan	714,556
Ohio	702,383
Missouri	155,175
Illinois	139,148

2.2.2 National Crop Data Layer 2009

The USDA, NASS Cropland Data Layer (CDL) is a raster, geo-referenced, crop-specific land cover data set with a ground resolution of 56 meters. The CDL is produced using satellite imagery collected during a given growing season. Some Cropland Data Layer states used additional satellite imagery to supplement the classification. Ancillary inputs to aid in classification include: the United States Geological Survey (USGS) National Elevation Dataset (NED), the USGS National Land Cover Dataset 2001 (NLCD 2001), and the National Aeronautics and Space Administration (NASA) Moderate Resolution Imaging Spectroradiometer (MODIS) Normalized Difference Vegetation Index (NDVI) composites. Training and validation data for accuracy assessments are derived from the Farm Service Agency (FSA) Common Land Unit (CLU) Program. The NLCD 2001 is used as non-agricultural training and validation data.

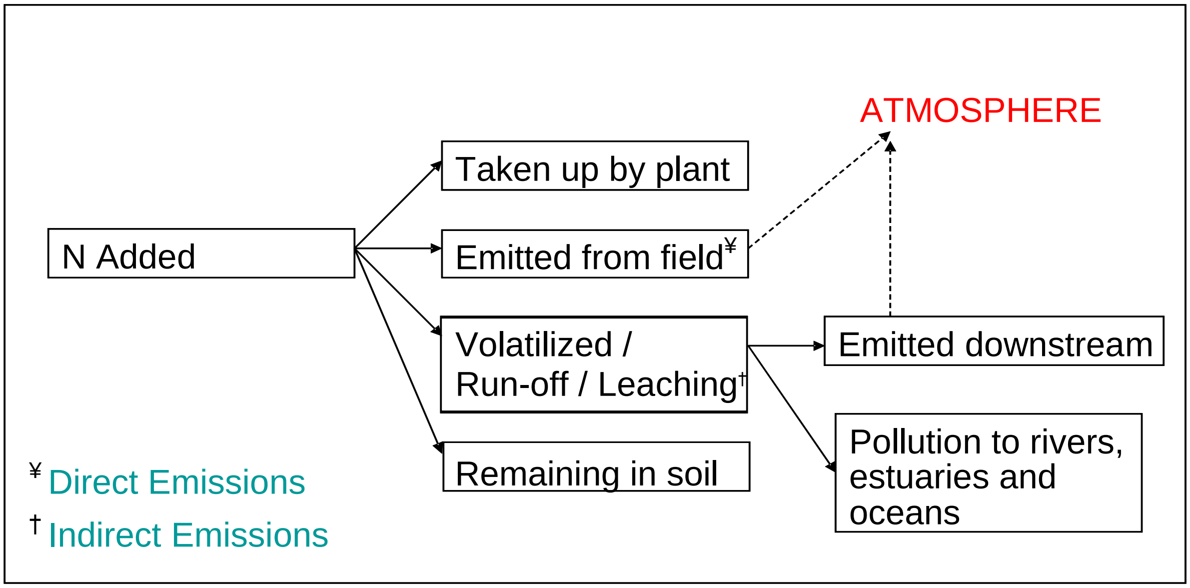
For each state the NCL was downloaded and the crops of interest to this analysis were isolated by reclassification. The crop categories from the CDL of interest are found in Table 2.

Table 2. Reclassification of varieties of the focus crops into single categories

RASTER VALUE	CLASS NAME	RECLASS
1	Corn	Corn
2	Cotton	Cotton
12	Sweet Corn	Corn
13	Popcorn or Ornamental Corn	Corn
22	Durum Wheat	Wheat
23	Spring Wheat	Wheat
24	Winter Wheat	Wheat

3.0 THEORETICAL BACKGROUND

As a gross simplification the nitrogen added to fields as fertilizer can have four broad destinations. It can be taken up by the plant, it can remain in the soil as an enhanced concentration of N, it can be emitted directly from the field into the atmosphere as nitrous oxide or it can leach down into the soil or run-off the top of the soil. The leached/runoff N can either continue downstream to cause pollution and/or it can be emitted into the atmosphere as nitrous oxide.



3.1 Approach to Calculation of Direct Emissions

Here we use a modified version of the Bouwman et al. (2002) model, referred to as the MBM, to account for direct and indirect N2O emisisons as described in the companion report from this work (Pearson and Brown 2010). The for the direct emissions, the MBM uses the following factors:

- Fertilizer rate
- Fertilizer type
- Crop type
- Soil texture
- Soil organic carbon content
- Drainage
- Soil pH
- Climate

The direct emissions are estimated as follows:

$$Emission = e^{-0.4136 + \sum_{1}^{n=1} \mathrm{Factorclass(i)}}$$

Where:

Emission= Nitrous oxide emission (N_2O-N); kg/ha

Factors:

- N-rate (kg/ha) * Fertilizer Type
- Crop Type
- Soil Texture
- Soil organic carbon content, %
- Soil drainage
- Soil pH
- Climate type
- Length of experiment
- Frequency of measurements

The parameters for the model are given in Table 3.

Table 3. Parameters for the MBM direct emissions.

Factor/Factor Class	N	Value
Constant		-0.4136
N-rate - Fertilizer Type Interaction		
AA – Anhydrous Ammonia	38	0.0056
AF – Ammonium-based Fertilizer	59	0.0051
AN – Ammonium Nitrate	117	0.0061
CAN – Calcium Ammonium Nitrate	61	0.0037
NF – Nitrate-based Fertilizers	53	0.0034
Mix – Mix of Various Fertilizers	25	0.0065
NP – Ammonium Phosphates	16	0.0039
U – Urea and Urine	98	0.0051
AM – Animal Manure	74	0.0021
AMF – Combinations of Animal Manure and Mineral N Fertilizers	41	0.0042
Crop type		
Grass	177	-1.268
Grass-clover	16	-1.242
Leguminous crops	36	-0.023
Other upland crops	512	0
Wetland rice	61	-2.536
Soil texture		
Coarse	447	-0.008
Medium	147	-0.472
Fine	134	0
Soil organic carbon, content, %		
SOC ≤ 1.0	92	0
1.0 < SOC ≤ 3.0	353	0.14
3.0 < SOC ≤ 6.0	126	0.58
SOC > 6	18	1.045
Soil drainage		
Poor	193	0
Good	460	-0.42
Soil pH		
pH ≤ 5.5	93	0
5.5 < pH ≤ 7.3	359	0.109
pH > 7.3	109	-0.352
Climate type		
Temperate	650	0
(Sub)Tropical	196	0.824
Length of experiment, days		
<120	343	0
120–180	132	0.004
180–240	42	0.487
240–300	34	0.657
>300	277	0.825
Frequency of measurements		
>1 meas/day	140	0
1 meas/day	286	0.125
1 meas/2– 3 day	78	1.639
1 meas/3– 7 day	262	0.825
<1 meas/week	46	0.788

Example calculation:

A wheat farm in Michigan applies 89 lbs per acre (or 99.8 kg/ha) of anhydrous ammonia fertilizer:

*99.8 (kg/ha) * 0.0056 = 0.5589*

With medium texture soils:	*-0.472*
2% organic carbon soils:	*0.14*
Poor drainage:	*0*
7.5 pH:	*-0.352*
Temperate:	*0*
1 year period:	*0.825*
Maximal measurements:	*0*

$$Emission = e^{-0.4136+0.5589+-0.472+0.14+0+-0.352+0+0.825+0}$$

= 1.33 kg N_2O-N/ha

Multiplied by 44/28[1] to calculate the N_2O emission

=2.09 kg N_2O/ha

Multiplied by 298[2] to derive a carbon dioxide equivalent

=624 kg CO_2-e/ha or 0.62 t CO_2-e/ha

When converted to per acre values the resulting estimate of direct emissions resulting from synthetic fertilizer application is:

0.25 t CO_2-e/ac

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[1] The ratio of molecular weights of N (nitrogen) to N_2O (nitrous oxide)

[2] The global warming potential of nitrous oxide according to the Intergovernmental Panel on Climate Change 4th Assessment Report (2007)

3.1.1 Fertilizer Use

The National Agricultural Statistics Service (NASS) is the statistical branch of the U.S. Department of Agriculture (USDA). NASS conducts hundreds of surveys, and issues nearly 500 national reports each year on topics such as agricultural production, economics, demographics and the environment. NASS also conducts the Census of Agriculture every five years. Producers, farm organizations, agribusinesses, lawmakers and government agencies all rely on the information produced by NASS.

We used the NASS data for state average fertilizer application in pounds per acre of fertilizer for each of the three crops in this analysis (Table 4). The year for the availability of data varied depending on the crop.

Table 4. State average annual rate of fertilizer application in pounds of nitrogen per fertilized acre.

2005 Corn

STATE	LBS/AC
Kentucky	171
Ohio	161
Missouri	160
Georgia	147
Indiana	147
Texas	147
Illinois	146
Iowa	141
Minnesota	139
Nebraska	138
Kansas	136
Colorado	129
North Carolina	124
North Dakota	121
South Dakota	113
Wisconsin	107
Pennsylvania	92
New York	67

2007 Cotton

STATE	LBS/AC
California	123
Mississippi	117
Arkansas	111
Tennessee	102
Missouri	97
South Carolina	91
Georgia	90
Alabama	88
Louisiana	87
Texas	82
North Carolina	68

2006 Wheat

STATE	LBS/AC
Idaho	121
Illinois	95
Missouri	94
Michigan	89
Ohio	89
Minnesota	88
Washington	82
North Dakota	69
South Dakota	69
Oregon	64
Texas	62
Kansas	57
Oklahoma	56
Nebraska	54
Montana	54
Colorado	31

3.1.2 Fertilizer Type

Personal communication with extension agents in Texas, Minnesota, Georgia, and Iowa revealed that price is the major factor in deciding which form of nitrogen to use. Due to current prices, anhydrous ammonia is the most common form used, especially for corn and for other instances where large amounts of nitrogen need to be applied (more than 100 lbs/ac). Urea is a common form for wheat but the second most common form overall is urea-ammonium nitrate at either 28-0-0 or 32-0-0 strength.

Three forms of nitrogen: anhydrous ammonia, urea, and urea-ammonium nitrate were modeled for all three crops.

3.1.3 Crop Type

The five crop classes used in the MBM are: grass, grass-clover, leguminous crops, other upland crops and wetland rice. Wheat, corn and cotton each are classified as other upland crops.

3.1.4 Soil Texture

Texture is a soil property used to describe the relative proportion of different sizes of mineral particles in a soil. Particles are grouped according to their size into what are called soil separates that are known as clay, silt, and sand. Texture classification is based on the fractions of separates present in a soil. A fourth term, loam, is used to describe a roughly equal concentration of sand, silt, and clay, and leads to even more classifications, e.g. "clay loam" or "silt loam." In the United States, the smallest particles are clay, the next smallest particles are silt, and the largest particles are sand.

We used STATSGO2 tables: chtexture and chtexturegrp to identify soil texture for each map-unit (polygon). The texture classes were reclassified into 2 emission categories: fine and coarse (Table 5, Figure 2).

Table 5. Reclassification of soil texture attribute values into emission categories (highest emissions associated with medium texture soils, medium emissions on coarse texture soils, and the lowest direct emissions on fine texture soils)

TEXTURE CLASS	RECLASS DESCRIPTION	RECLASS CODE
Clay	Fine	1
Clay loam	Fine	1
Coarse sand	Coarse	2
Coarse sandy loam	Coarse	2
Fine sand	Coarse	2
Fine sandy loam	Coarse	2
Loam	Coarse	2
Loamy coarse sand	Coarse	2
Loamy fine sand	Coarse	2
Loamy sand	Coarse	2
Loamy very fine sand	Coarse	2
Sand	Coarse	2
Sandy clay	Coarse	2
Sandy clay loam	Coarse	2
Sandy loam	Coarse	2
Silt	Medium	3

TEXTURE CLASS	RECLASS DESCRIPTION	RECLASS CODE
Silt loam	Medium	3
Silty clay	Coarse	2
Silty clay loam	Coarse	2
Very fine sandy loam	Coarse	2
All other types (muck, bedrock, etc)	Background	0

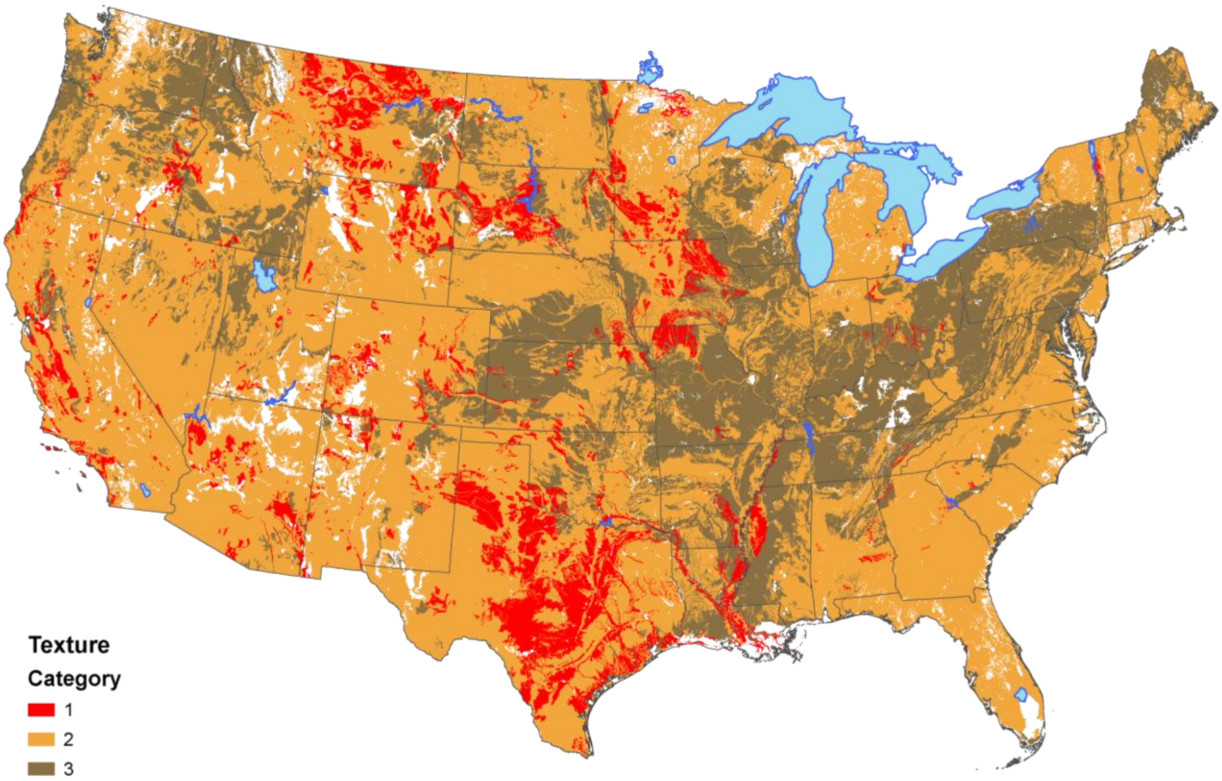

Figure 2. Soil texture categories, reclassified into emission rankings (1 = lowest, 2 = medium and 3 = highest emissions).

3.1.5 Organic Material

In STATSGO2, organic material values in the tables are defined by the metadata as being “the amount by weight of decomposed plant and animal residue expressed as a weight percentage of the less than 2 mm soil material.” (USDA). Each percent of organic matter in the soil releases 20 to 30 pounds of nitrogen per year (Funderburg 2001).

The STATSGO2 table “chorizon” was used to identify and categorize organic material for each mapunit (polygon) . The column “ph1to1h2o_r “ in the data base is the representative value for the mapunit. The MBM uses soil organic matter expressed in units of soil carbon, and to convert to soil carbon we used the following factor: Organic Carbon (%) = Organic Matter (%) / 1.724

The soil organic material converted to organic carbon was reclassified into 3 emission categories; low (<1%), medium (1% - 6%), high(>6%) (Table 6, Figure 3).

Table 6. Reclassification of soil organic carbon material attribute values into emission categories.

Organic Carbon (%)	RECLASS DESCRIPTION	RECLASS CODE
> 6	High	1
3.1 - 6	High Medium	2
1.1 - 3	Low Medium	3
≤1	Low	4
(blank)	Background	0

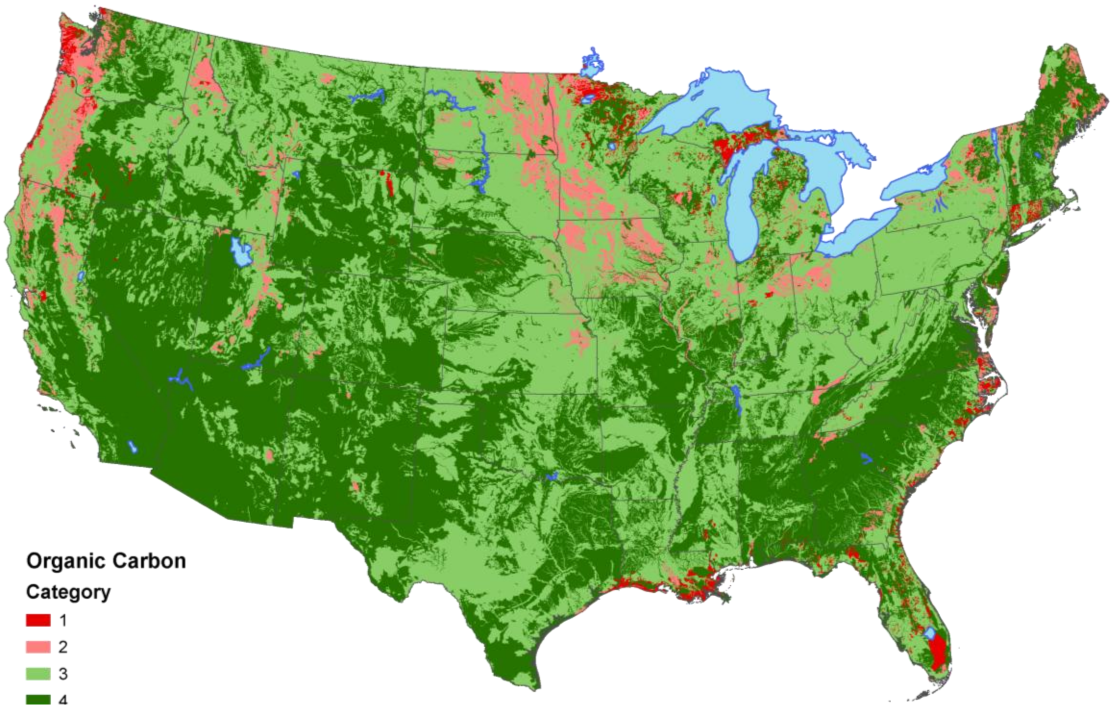

Figure 3. Soil organic material categories, converted to organic carbon and reclassified into emission rankings. 1 = highest emission rank and 4 = lowest emission rank.

3.1.6 Drainage

Drainage is the natural or artificial removal of surface and sub-surface water from an area. Agricultural soils need drainage to improve production or to manage water supplies. Drainage is important to nitrogen emissions because poor drainage is shown to increase the nitrogen emission rate.

The STATSGO2 tables “table component and column drainagecl” were used to identify for each mapunit (polygon) the drainage properties. The drainage values were reclassified into 2 emission categories; poorly drained and well drained (Table 7, Figure 4). Poor drainage has the highest emissions and good drainage has the lowest.

Table 7. Reclassification of soil drainage attribute values into emission categories.

DRAINAGE CLASS	RECLASS DESCRIPTION	RECLASS CODE
Excessively drained	Good	2
Moderately well drained	Good	2
Poorly drained	Poor	1
Somewhat excessively drained	Good	2
Somewhat poorly drained	Poor	1
Very poorly drained	Poor	1
Well drained	Good	2
(blank)	Background	0

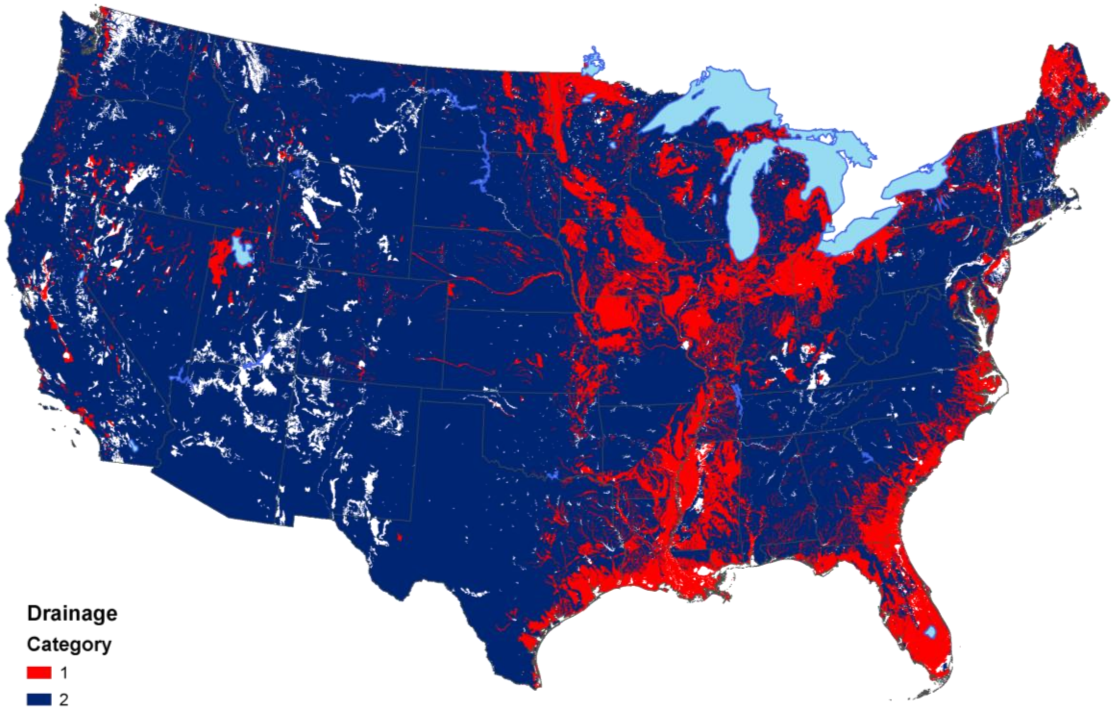

Figure 4. Soil drainage categories, reclassified into emission rankings with 1 = poorly drained and high emission rank and 2 = well drained and low emission rank.

3.1.7 Soil pH

Soil pH is a measure of the soil acidity or soil alkalinity and is influenced by the soil parent materials. It is an important consideration for farmers and the majority of food crops prefer a neutral or slightly acidic soil. Some plants, however, prefer more acidic (e.g., potatoes, strawberries) or alkaline (e.g., cabbage, broccoli) conditions. Rainfall also affects soil pH. Water passing through the soil leaches basic nutrients such as calcium and magnesium from the soil. They are replaced by acidic elements such as aluminium and iron. For this reason, soils formed under high rainfall conditions are more acidic than those formed under arid (dry) conditions. Soil acidity is reduced by volatilization and denitrification of nitrogen. Under flooded conditions, the soil pH value increases. In addition, the following nitrate fertilizers -- calcium nitrate, magnesium nitrate, potassium nitrate and sodium nitrate -- also increase the soil pH value.

We used STATSGO2 table “chorizonto” to identify for each mapunit (polygon) a pH value from the column “ph1to1h2o _r”. The column ph1to1h2o_r is the representative pH value for the mapunit. The pH values were reclassified into three emission categories; medium (<5.5), high (5.5-7.3), low(>7.3) (Table 8, Figure 5)

Table 8. Reclassification of soil pH attribute values into emission categories. Highest emissions occur on neutral soils, medium emissions on low pH soils, and lowest emissions on alkaline soils.

pH	RECLASS DESCRIPTION	RECLASS CODE
< 5.5	Medium	2
5.5 – 7.3	High	1
> 7.3	Low	3
(blank)	Background	0

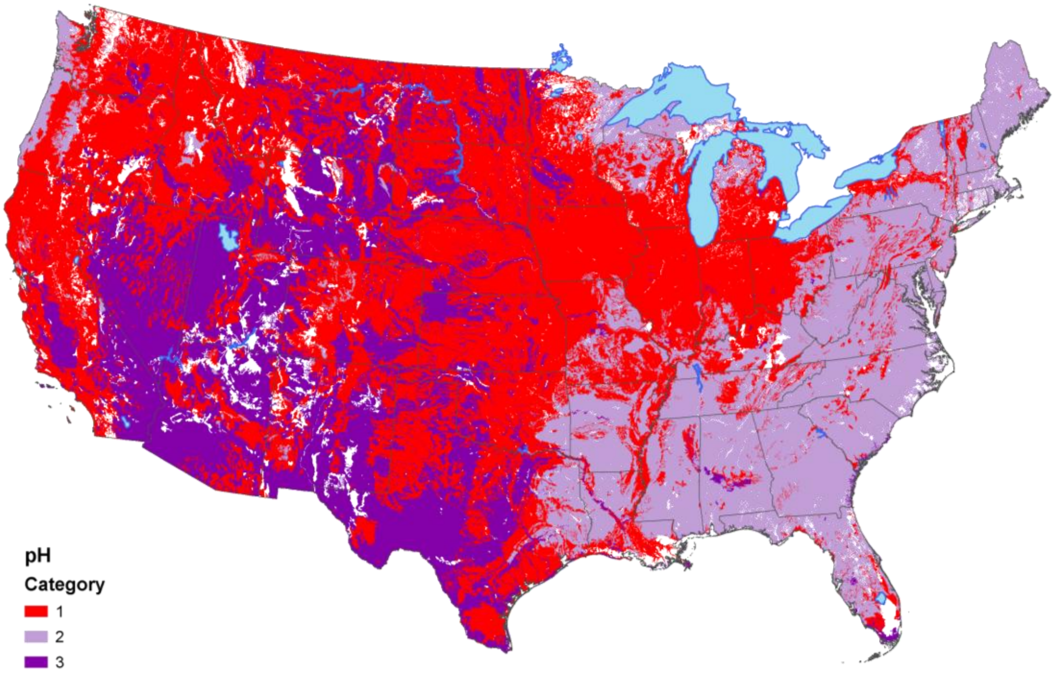

Figure 5. Soil pH categories, reclassified into emission rankings. 1 = high emission rank, 2 = medium emisison rank, and 3 = low emission rank.

3.1.8 Climate type

The climate type throughout agricultural lands in the US is simply classified as temperate.

3.1.9 Length of experiment

The length of the experiment is considered to be a year to allow annual accounting.

3.1.10 Frequency of measurements

The maximum frequency of measurements is assumed to capture all potential emissions.

3.2 Approach to Indirect Emissions

As with direct emissions, the method used here is based on the companion report by Pearson and Brown (2010). The general form of the equations follows the IPCC approach with a site-specific improvement to include emissions resulting from leaching.

Indirect Emissions = Emissions from leaching of NO3- + Emissions from volatilization & deposition of NH4+

3.2.1 Emissions resulting from leaching

Emission resulting from leaching = Amount of fertilizer applied * Fraction Leaching * Emission Factor

3.2.1.1 Amount of fertilizer applied

See Section 3.1.1 for the quantity of fertilizer applied by crop and by state.

3.2.1.2 Fraction leaching

Where annual rainfall is less than potential evapotranspiration then:

FRACLEACH = 0.05 (IPCC default)

Otherwise:

$$FRACLEACH = PRF * RF * F$$

Where:

F = Leaching factor based on presence or absence of tile drainage, tillage and deep-rooted crops

RF = Leaching factor based on precipitation in current year of N_2O emission assessment

PRF = Leaching factor based on precipitation in year prior to current N_2O emission assessment

F =

If + Tile + Till - Deep-Rooted = 0.30

If	- Tile	+ Till	- Deep-Rooted	or		
	+ Tile	- Till	- Deep-Rooted	or		
	+ Tile	+ Till	+ Deep-Rooted		=	0.20
If	- Tile	- Till	- Deep-Rooted	or		
	- Tile	+ Till	+ Deep-Rooted	or		
	+ Tile	- Till	+ Deep-Rooted		=	0.15
If	- Tile	- Till	+ Deep-Rooted		=	0.125

Where:

Tile = presence (+) or absence (-) of tile drainage
Till = presence (+) or absence (-) of tillage as part of agricultural practices
Deep-rooted = presence (+) or absence (-) of deep-rooted crop in assessment year

$$RF = \frac{AR}{MAR}$$

Where:

AR = Annual rainfall; inches
MAR = Mean annual rainfall; inches

PRF =

If previous year's rainfall = < ½ MAR and AR > MAR = 2
otherwise = 1

3.2.1.2.1 Tile drainage

Modern production agriculture in much of the central and eastern United States would not be possible without the extensive drainage network that has been built up starting ~1870. While an unqualified success for increasing agricultural production, much of the nitrate that enters the Mississippi river and contributes to hypoxia in the northern Gulf of Mexico comes from tile drainage of agricultural fields in the Midwest. (Jaynes and James 2007). Unfortunately, little institutional information about the location and extent of tile drained cropland in the US is known. This analysis follows the methods of Jaynes et al. by using the direct emission factor of drainage as a guide to whether a field is in tile drainage or has a potential for being converted to tile drainage (Fig. 3). Where the direct emission factor drainage was classified as poor, then tile drainage was assumed to be present otherwise it is assumed to be absent.

3.1.1.2.2 Tillage

In all cases tillage is assumed to occur.

3.1.1.2.3 Rooting depth

Wheat, corn and cotton are all considered to be deep-rooted crops.

3.1.1.2.4 Rainfall

For the purpose of the calculations, rainfall is assumed to be equal to mean annual rainfall, so that AR (annual rainfall) and MAR (mean annual rainfall) are considered to be identical.

3.2.1.3 Emission factor

The IPCC report gives a range of values for the emissions factor of 0.0005 to 0.025. There is no literature to support under what conditions a particular value for the emission factor should be chosen. We therefore chose to use the suggested IPCC value of 0.0075 in the calculations.

3.2.2 Emissions resulting from volatilization

Emissions resulting from volatilization = Amount of fertilizer applied * Volatilization Fraction * Emission Factor

Leaching and run-off account for 75% of indirect emissions, with atmospheric deposition only a fifth of the magnitude of emissions due to leaching (Nevison 1999). Studies on this form of indirect emission are very limited and are largely focused on forest soils. We use the IPCC defaults for fraction volatilized and proportion of redeposited fraction that is emitted as N_2O.

The amount of fertilizer used comes from the sources described in section 3.1.1. The IPCC set the fraction volatilized to be equal to 0.1. The IPCC default value for the volatilized proportion emission factor was set equal to 0.01.

3.3 Combining the data

The three soil variables were then combined with the crop variable and a US county data layer using the intersect function to create a single file. This creates a single file where at any given location the values of all variables are known and therefore the nitrogen emission for that location can be calculated. The equations used to calculate the total annual nitrogen emissions are:

1. **Calculate direct nitrogen emission**

= EXP(-0.4136+(0.0053* [fertilizer_amount])+ [texture_emission]+ [oc_emission]+ [drainage_emission]+0.825)

2. **Convert to CO_2-e**

Equivalent_emission=((direct _emission*(44/28))*298)/1000

3. **Incorporate indirect nitrogen emission to total emissions**

=(equivalent _emission +(equivalent _emission *leaching)+(equivalent _emission *volatilization)

4.0 RESULTS

Emission values ranged between 0.12 and 1.45 t CO_2-e per acre annually. Corn farms show higher emissions than either cotton or wheat and the range between maximum and minimum - 1.25 t CO_2-e/ac - is the largest of all three crops. For all three crops, anhydrous ammonia has the highest emission values and urea has the lowest (Table 9). However, as the difference in emissions among the different fertilizer types per crop is not particularly large, maps of the spatial distribution will be presented only for anhydrous ammonia fertilizer as this is commonly used and is the cheapest.

Table 9. Summary results, in average annual t CO_2-e per acre, across crops, locations and fertilizer types

		Corn	Cotton	Wheat
Mean	Anhydrous Ammonia	0.53	0.38	0.34
	Urea and Urine	0.49	0.36	0.33
	Urea Ammonium Nitrate	0.50	0.36	0.33
Maximum		1.45	0.97	0.93
Minimum		0.19	0.16	0.12
90% Confidence Interval		0.01	0.01	0.01

Applying the the per acre values to the area of each crop in each county gives an estimate of annual national emissions, across the three crops in the 31 states, of between 57.4 million tons of carbon dioxide equivalent (urea and urine) and 61.4 million t CO_2-e (anhydrous ammonia). For all fertilizers approximately 70% of the total emissions were from corn fields, 25% from wheat fields and 5% from cotton fields.

Geographically, the locations with the highest emissions for all crops are spatially related to the location of the four key soil emission factors, however, there is variability among the crops. Soil organic matter is the dominant factor for corn and wheat but for cotton, texture is the dominant factor. This is likely due to the greater variability in values for the texture factor in cotton-growing areas whereas corn and wheat see a more homogenous texture but greater variability with organic matter and drainage.

4.1 Corn

There are 1,744 counties in 19 states growing corn, the largest number of counties of the three crops. The highest emissions for corn occur with anhydrous ammonia fertilizers, with a mean of 0.53 t CO_2-e/acre annually. The location of the highest emissions is in the upper Midwest, starting in northeast Iowa the high emission trend continues northwest into Minnesota and North Dakota (Figures 7 and 8). Other areas of high emissions occur in northern Ohio and northeastern Indiana, along the Atlantic coast of North Carolina and Georgia and the Gulf Coast of Texas. This follows the trend of the organic matter factor (Figure 3), where category 2 shows the same trend in the upper Midwest and where category 1 (highest emissions) occurs most frequently along coastal areas and along the shores of the Great Lakes. The next highest emissions come from Urea Ammonium Nitrate and the locations of the highest emissions follow the same pattern as AA. Out of the 19 states in the corn group, the state with the highest average emission is Iowa at 0.77 tons CO_2-e per acre annually. There is no strong evidence of a connection between amount of fertilizer applied and emissions based on the results of this model. Kentucky which has the highest average use of fertilizer, 171 lbs/ac (Table 3), ranks

10th in emissions (Tables 10 and 11) and while Ohio is second in fertilizer usage and ranks second in emissions, Missouri is sixth in emissions despite ranking third in fertilizer usage.

Table 10. Estimated annual per acre nitrous oxide emissions by potential fertilizer type on corn fields in the United States (t CO_2-e/ac).

STATE	Anhydrous Ammonia	Urea and Urine	Urea- Ammonium Nitrate
Iowa	0.77	0.71	0.73
Ohio	0.70	0.64	0.66
Minnesota	0.66	0.61	0.63
Indiana	0.62	0.57	0.59
Illinois	0.60	0.55	0.57
Missouri	0.56	0.51	0.53
Georgia	0.55	0.51	0.52
North Dakota	0.55	0.51	0.53
North Carolina	0.53	0.49	0.51
Kentucky	0.52	0.47	0.49
Texas	0.50	0.46	0.47
Nebraska	0.46	0.43	0.44
Kansas	0.45	0.42	0.43
South Dakota	0.44	0.41	0.42
Colorado	0.41	0.38	0.39
Wisconsin	0.39	0.37	0.38
New York	0.31	0.30	0.31
Pennsylvania	0.31	0.29	0.30
National Mean	0.53	0.49	0.50

Table 11. Estimated total annual nitrous oxide emissions by potential fertilizer type on corn fields in the United States (t CO_2-e).

STATE	Anhydrous Ammonia	Urea and Urine	Urea- Ammonium Nitrate
Iowa	9,805,800	9,060,800	9,351,800
Illinois	6,958,100	6,411,500	6,624,800
Minnesota	4,807,900	4,447,600	4,588,400
Nebraska	3,849,100	3,562,600	3,674,600
Indiana	3,412,900	3,143,000	3,248,300
Ohio	2,370,800	2,166,300	2,245,900
South Dakota	2,050,700	1,924,800	1,974,200
Missouri	1,738,300	1,589,300	1,647,300
Kansas	1,634,000	1,514,100	1,561,000
North Dakota	1,324,000	1,237,200	1,271,200
Texas	1,260,700	1,161,000	1,199,900
Wisconsin	1,247,300	1,174,700	1,203,200
North Carolina	558,100	520,600	535,300
Kentucky	535,500	486,600	505,600
Colorado	474,300	441,200	454,200
New York	415,400	400,100	406,100

STATE	Anhydrous Ammonia	Urea and Urine	Urea- Ammonium Nitrate
Pennsylvania	302,100	286,900	292,900
Georgia	204,900	188,700	195,000
National Total	42,949,900	39,716,900	40,979,500

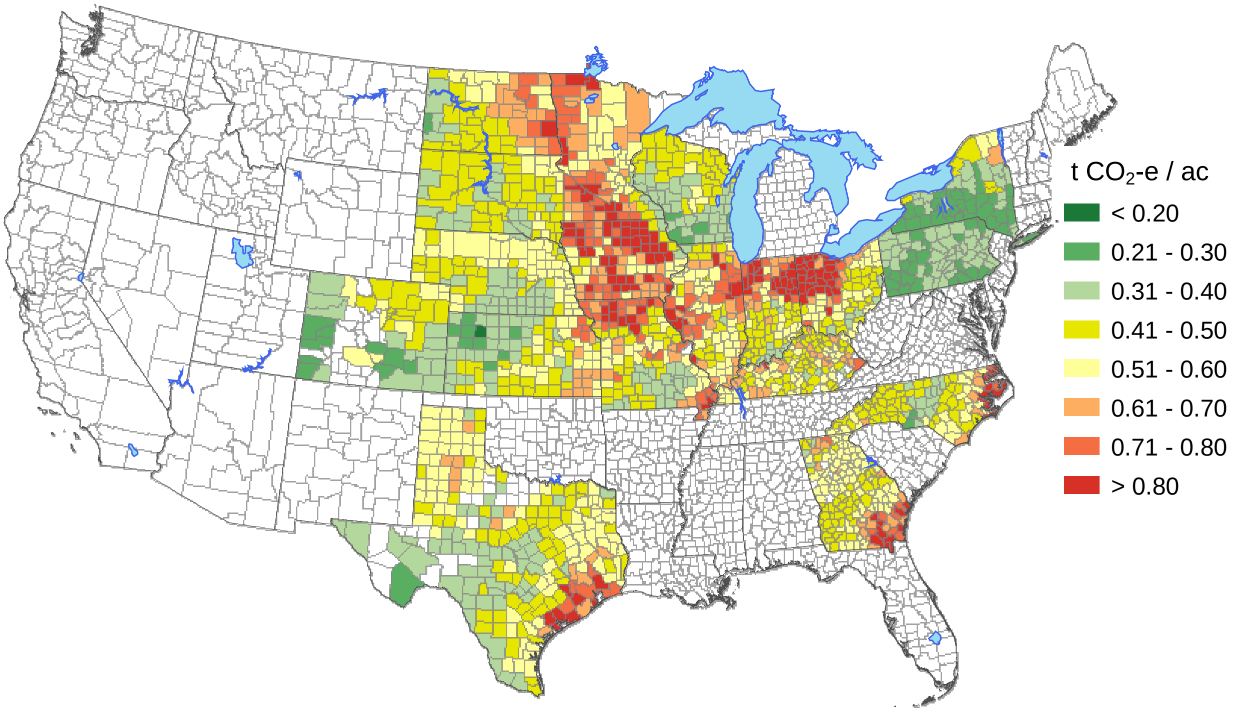

Figure 7. Estimated annual emissions t CO_2-e/acre from corn fields for anhydrous ammonia fertilizer

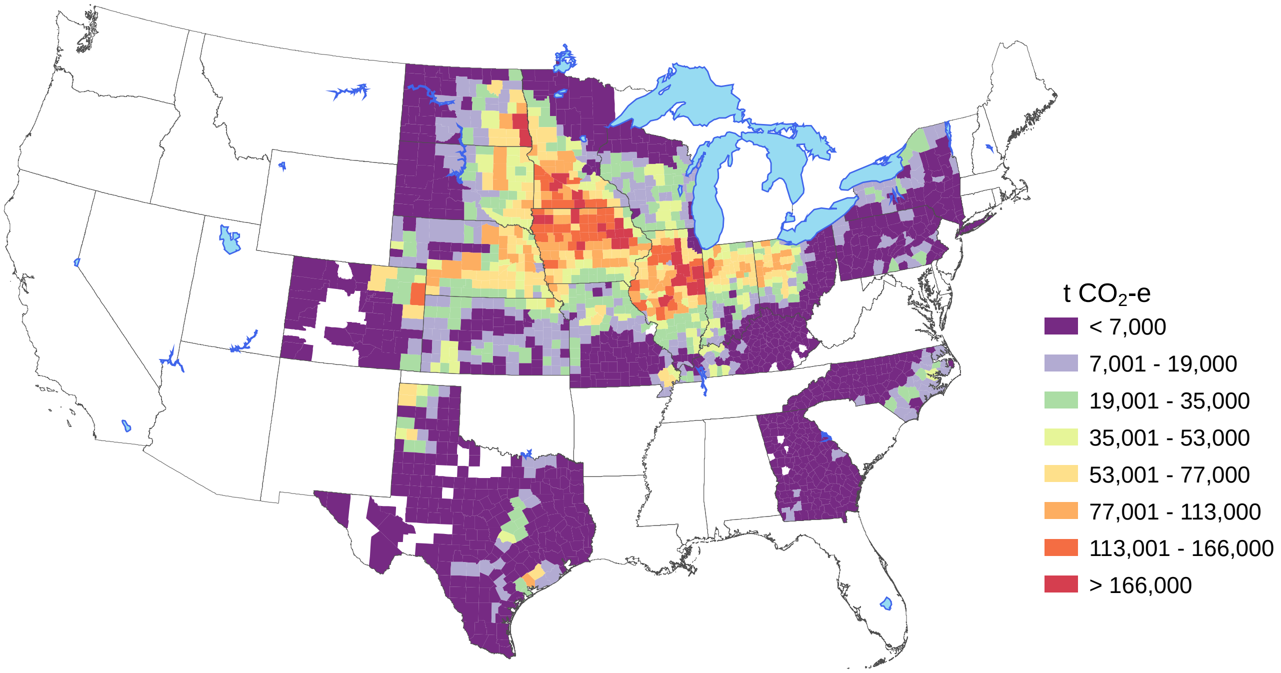

Figure 8. Estimated cumulative county-level annual emissions from corn fields for anhydrous ammonia fertilizer

4.2 Cotton

There were 11 cotton growing states and, with just under a total of 800 counties, cotton formed the smallest group in this analysis in terms of area. The mean annual emission is highest with anhydrous ammonia at 0.38 t CO_2-e/ac followed by UAN and U at 0.36 CO_2-e/ac (Tables 12 and 13). As with corn, the highest emissions occur in counties with wet soils. Unlike corn, the texture factor is more dominant in determining emissions. In the case of cotton, highest emissions occur in counties along the Atlantic coast, Mississippi River and Gulf Coast. California has the highest fertilizer use but ranks 8th in emissions while Mississippi with the second most use of fertilizer ranks first in emissions. Mississippi can be expected to have high emissions with so much of the cotton farm land located along the river basin.

Table 12. Estimated annual per acre nitrous oxide emissions by potential fertilizer type on cotton fields in the United States (t CO_2-e / ac)

STATE	Anhydrous Ammonia	Urea and Urine	Urea- Ammonium Nitrate
Mississippi	0.50	0.46	0.48
Missouri	0.46	0.43	0.44
North Carolina	0.40	0.39	0.39
South Carolina	0.40	0.38	0.39
Louisiana	0.39	0.38	0.38
Arkansas	0.39	0.37	0.38
Georgia	0.39	0.37	0.38
California	0.39	0.36	0.37
Alabama	0.35	0.34	0.34
Texas	0.33	0.31	0.32
Tennessee	0.30	0.29	0.29
National Mean	0.38	0.36	0.36

Table 13. Estimated total annual nitrous oxide emissions by potential fertilizer type on cotton fields in the United States (t CO_2-e)

STATE	Anhydrous Ammonia	Urea and Urine	Urea- Ammonium Nitrate
Texas	1,867,000	1,783,100	1,816,200
Georgia	354,700	337,300	344,200
North Carolina	186,500	179,600	182,300
Arkansas	184,600	173,400	177,800
Mississippi	152,300	142,600	146,400
Missouri	133,000	126,000	128,700
Louisiana	91,000	86,700	88,400
California	81,200	75,800	77,900
Alabama	77,700	73,900	75,400
Tennessee	65,400	61,800	63,200
South Carolina	38,000	36,100	36,800
National Total	3,231,400	3,076,300	3,137,400

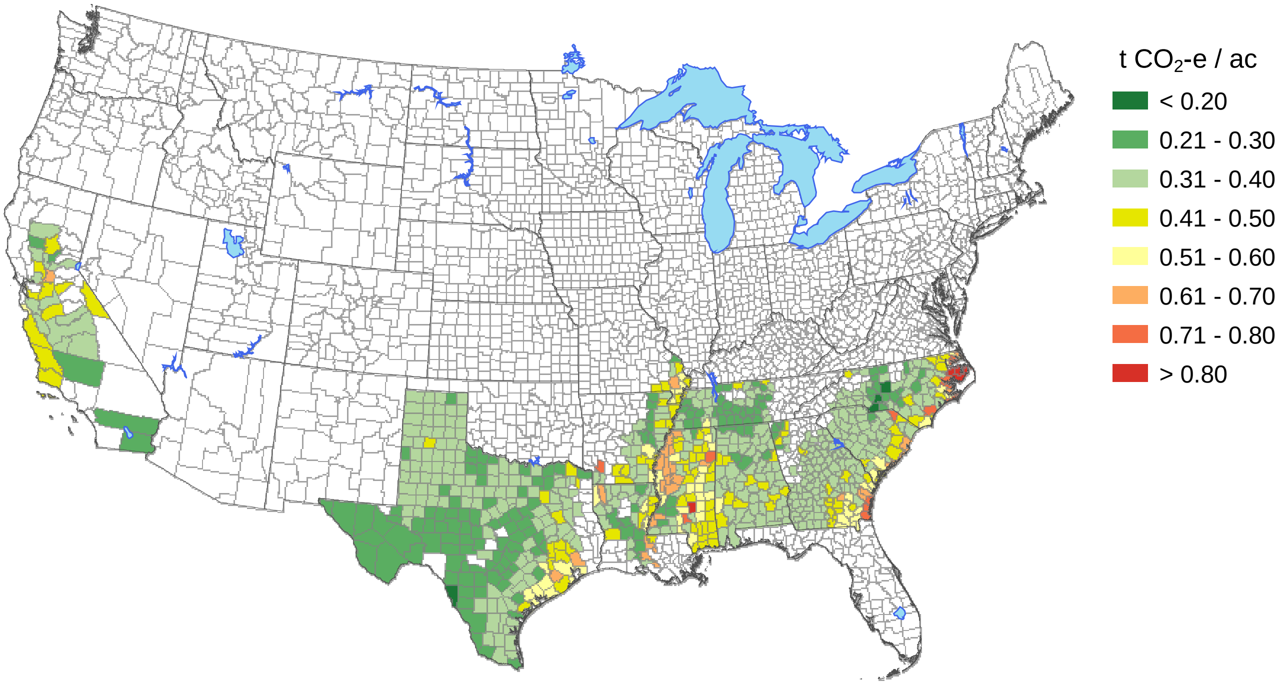

Figure 10. Estimated annual emissions, t CO_2-e/acre from cotton fields for anhydrous ammonia fertilizer

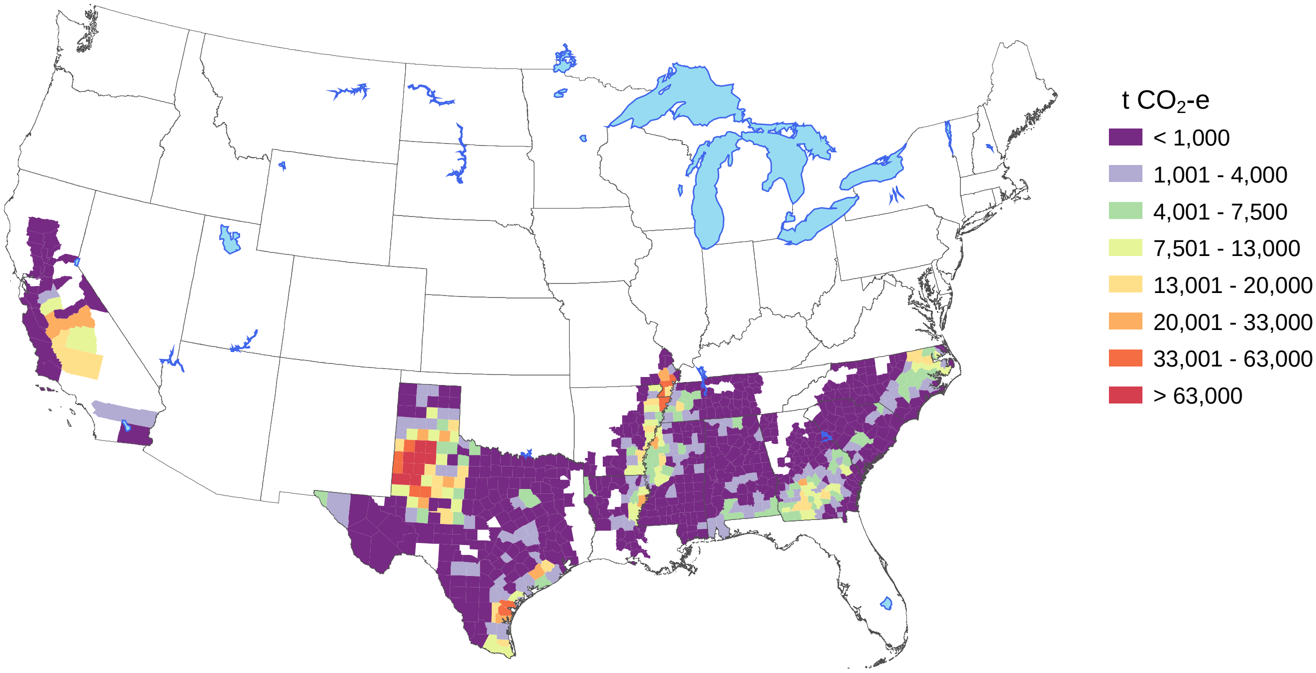

Figure 11. Estimated cumulative county-level annual emissions from cotton fields for anhydrous ammonia fertilizer

4.3 Wheat

Wheat has the lowest average annual emissions per acre of the three crops. There are 16 states and 1,340 counties with wheat farms in this analysis with a mean calculated emission of 0.34 t CO_2-e/acre for AA fertilizers, and 0.33 t CO_2-e/acre for both UAN and urea (Tables 14 and 15). Minnesota and Michigan are tied for the highest emissions when the fertilizer is AA and U but Minnesota has the highest emission marginally when fertilization is with UAN. Minnesota ranks 6th in fertilizer application amounts (Table 3) while conversely Idaho, which ranks 1st in fertilizer amounts, ranks 8th in emissions (Tables 14 and 15). Specific locations of high emissions are found in Michigan's Upper Peninsula, northwest Ohio, and eastern North Dakota along the border with Minnesota. These areas are also locations of the highest organic material factor categories, class 1 or 2. Like corn, wheat emission values are more heavily influenced by organic material then any other factor.

Table 14. Estimated annual per acre nitrous oxide emissions by potential fertilizer type on wheat fields in the United States (t CO_2-e/ac)

STATE	Anhydrous Ammonia	Urea and Urine	Urea- Ammonium Nitrate
Minnesota	0.48	0.46	0.47
Michigan	0.48	0.46	0.46
Ohio	0.44	0.42	0.43
Illinois	0.43	0.40	0.41
North Dakota	0.41	0.39	0.40
Missouri	0.35	0.33	0.34
South Dakota	0.34	0.32	0.33
Idaho	0.33	0.31	0.32
Oregon	0.32	0.31	0.31
Washington	0.31	0.30	0.30
Texas	0.29	0.28	0.28
Montana	0.27	0.26	0.27
Kansas	0.27	0.26	0.27
Oklahoma	0.27	0.26	0.26
Nebraska	0.26	0.26	0.26
Colorado	0.23	0.22	0.22
National Mean	0.34	0.33	0.33

Table 15. Estimated total annual nitrous oxide emissions by potential fertilizer type on wheat fields in the United States (t CO_2-e)

STATE	Anhydrous Ammonia	Urea and Urine	Urea- Ammonium Nitrate
North Dakota	3,612,300	3,475,300	3,529,400
Kansas	2,031,600	1,967,700	1,993,000
Texas	1,877,600	1,813,500	1,838,900
Montana	1,545,700	1,499,600	1,517,900
Oklahoma	1,301,500	1,261,300	1,277,300
Minnesota	941,500	896,200	914,100
South Dakota	827,400	796,000	808,400
Washington	573,400	547,600	557,800
Colorado	569,000	559,200	563,100
Ohio	435,800	414,600	422,900
Idaho	424,600	396,800	407,700
Michigan	387,800	368,900	376,400
Nebraska	321,400	311,900	315,700
Oregon	233,500	225,200	228,500
Illinois	64,900	61,500	62,800
Missouri	56,100	53,200	54,400
National Total	15,204,000	14,648,500	14,868,100

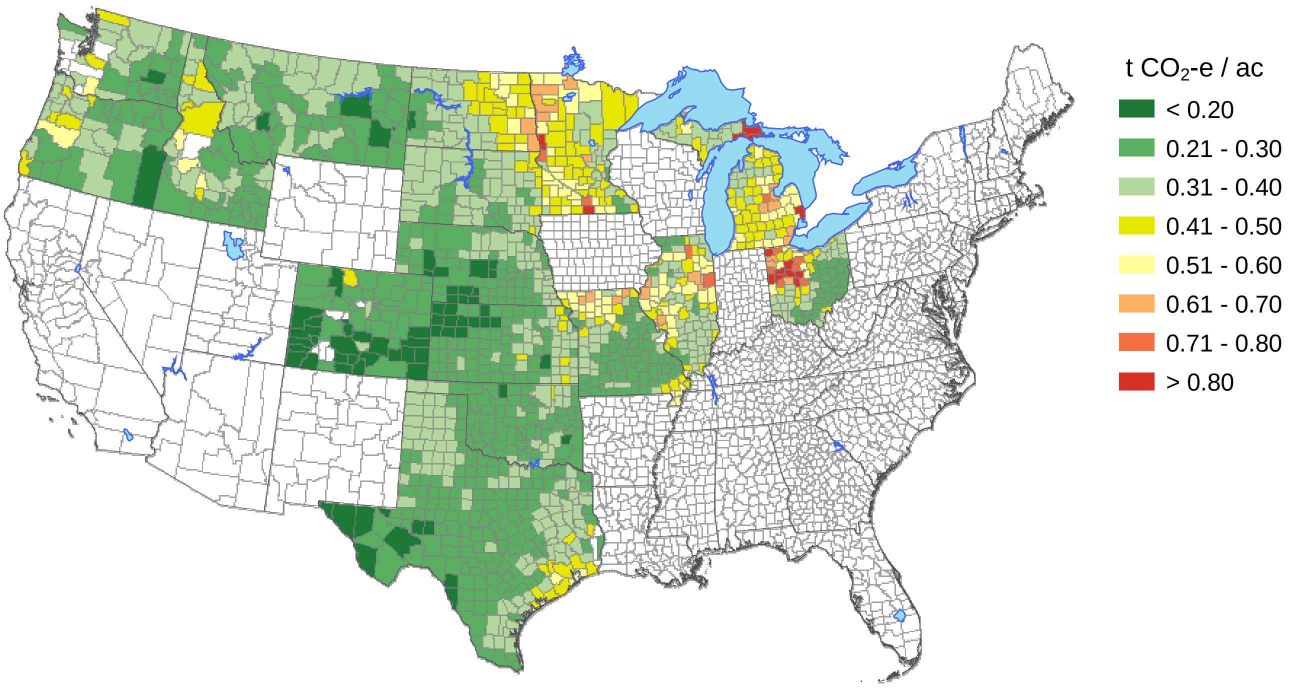

Figure 13. Estimated annual emissions, t CO_2-e/acre, from wheat fields for anhydrous ammonia fertilizer

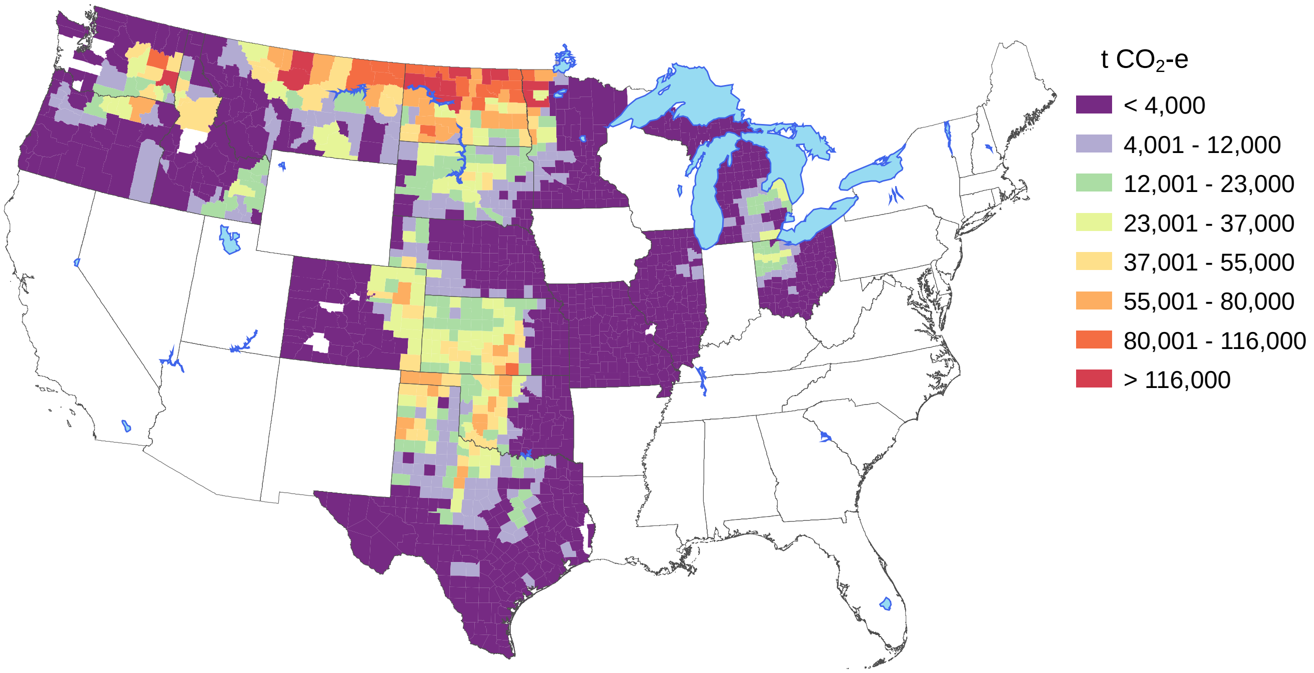

Figure 14. Estimated cumulative county-level annual emissions, t CO_2-e from wheat fields for anhydrous ammonia fertilizer

5.0 SUMMARY

5.1 Spatial Summary

Iowa leads the nation by a wide margin in annual emissions despite only growing one of the three crops analyzed here, corn (Figure 15). The next two states are Illinois and Minnesota, both of which grow two crops, corn and wheat. Texas which grows all three crops comes in fourth in total annual emissions.

Summarizing the data across all three crops for total annual emissions reveals Iroquois county, Illinois as the leading county in the nation for annual emissions with over 383,000 t CO_2-e. This leads the second highest county, McLean, Illinois by over 118,000 t CO_2-e (Table 16). These two counties grow both corn and wheat as do all the other counties in the top ten that are not located in Iowa.

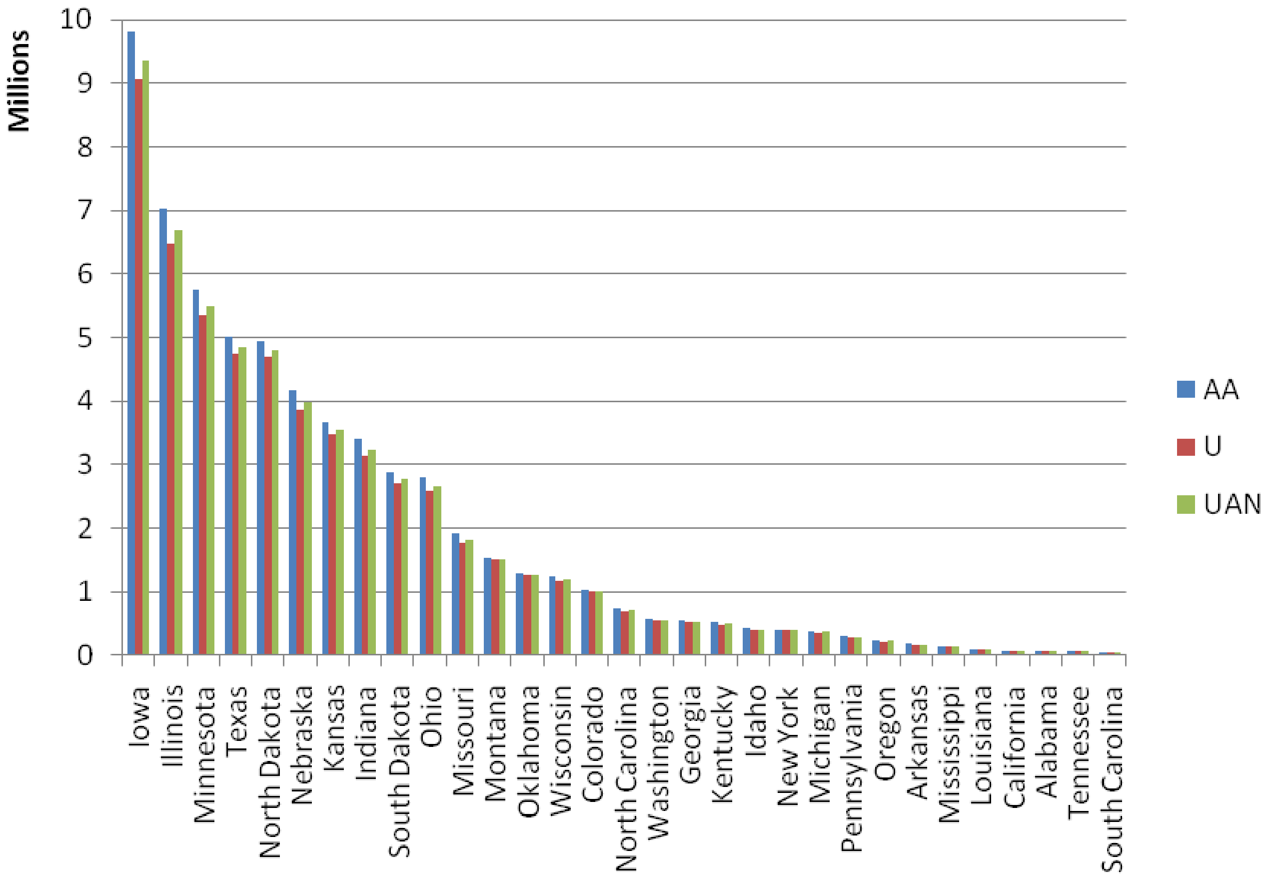

Figure 15. Summed nitrous oxide emissions by State in t CO_2-e from cultivation of corn, wheat and cotton. AA = anhydrous ammonium; U = urea and urine; UAN = Urea ammonium nitrate

Table 16. Top ten counties for estimated total annual emissions in the United States (t CO_2-e) for anhydrous ammonia fertilizer only.

STATE	COUNTY	Annual Emission
Illinois	Iroquois	384,000
Illinois	McLean	265,400
Iowa	Sioux	260,700
Illinois	Livingston	250,000
North Dakota	Cass	242,600
Iowa	Kossuth	235,900
North Dakota	Richland	232,600
Iowa	Buchanan	230,000
North Dakota	Cavalier	219,700
Minnesota	Renville	218,100

The same geographic trend for emissions can been seen with the combined total emissions as with the individual crop emissions; starting with Illinois and moving northwest through Iowa and western Minnesota into North Dakota. This area has the highest and the most contiguous area of high emissions in the nation (Figure 16).

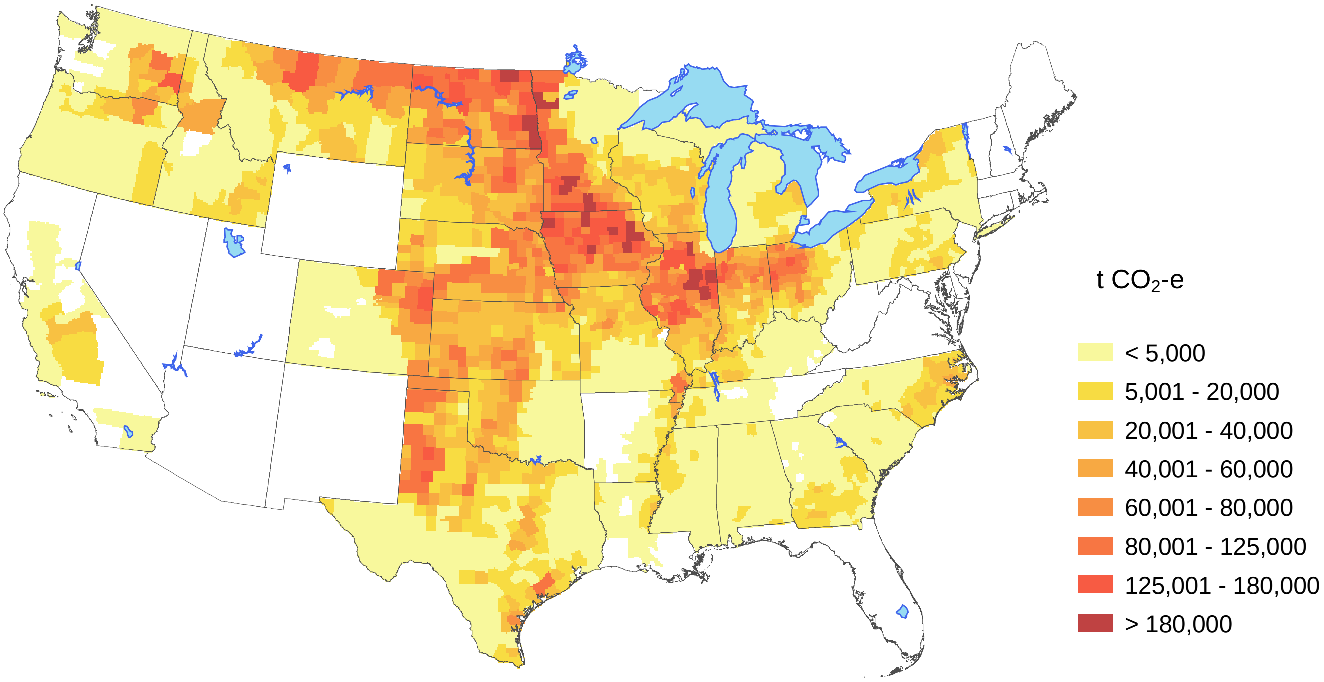

Figure 16. Estimated total county-level annual emissions of nitrous oxide from all crops for anhydrous ammonia fertilizer, in t CO$_2$-e.

5.2 Statistical Analysis of Results

The emissions distribution for all three crops is non-normal (Figures 17, 18 and 19; Tables 17, 18 and 19). This means that the plot of frequency of emission values is skewed right with a tail of high emissions values stretching away from the mean that is not matched by a similar pattern of low emission values. Cotton is the most skewed. The results also show that cotton and corn have kurtosis values above three meaning the values in the data change abruptly or if looked at in a histogram the peaks and valleys in the values are jagged. Wheat has a kurtosis value near three meaning the data value changes less abruptly and shows a greater smoothness to value changes over the other two crops.

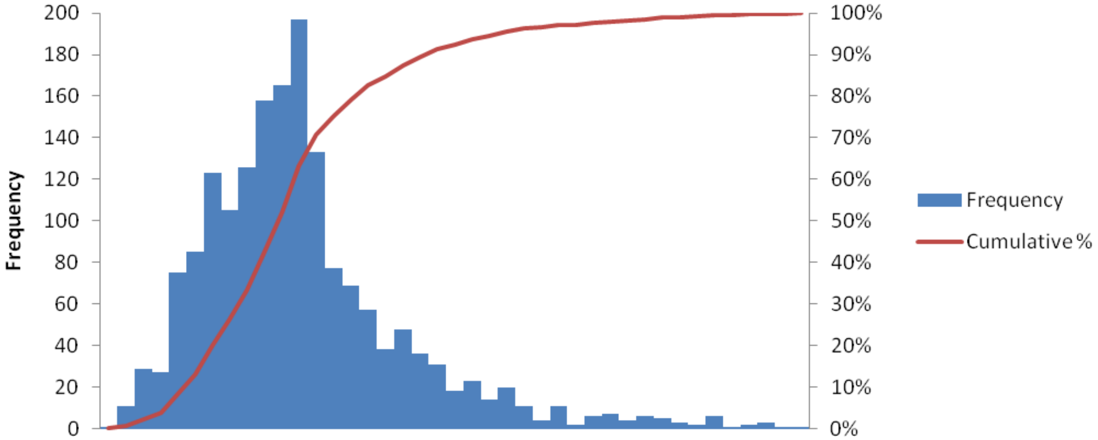

Figure 17. Histogram of corn emission values for anhydrous ammonia

Table 17. Summary statistics for results for each potential fertilizer type on corn farms (t CO_2-e/ac)

	Anhydrous Ammonia	Urea and Urine	Urea- Ammonium Nitrate
Mean	0.53	0.49	0.50
Standard Error	0.004	0.004	0.004
Median	0.50	0.46	0.48
Mode	0.52	0.48	0.50
Standard Deviation	0.18	0.17	0.17
Sample Variance	0.034	0.028	0.030
Kurtosis	3.38	3.41	3.40
Skewness	1.49	1.52	1.51
Range	1.25	1.14	1.18
Minimum	0.20	0.19	0.19
Maximum	1.45	1.33	1.37
Confidence Interval (95%)	0.01	0.01	0.01

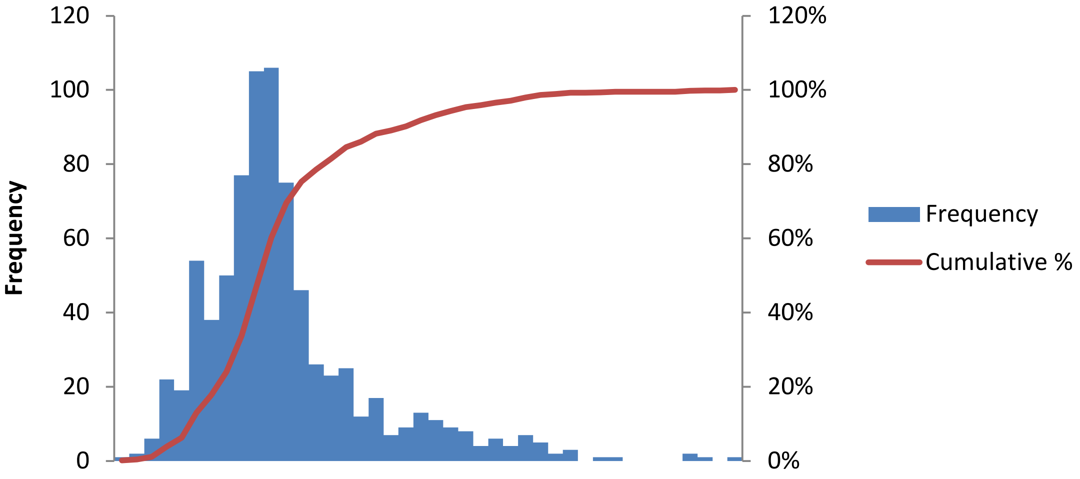

Figure 18. Histogram of cotton emission values for anhydrous ammonia

Table 18. Summary statistics for results for each potential fertilizer type on cotton farms (t CO_2-e / ac)

	Anhydrous Ammonia	Urea and Urine	Urea- Ammonium Nitrate
Mean	0.38	0.36	0.36
Standard Error	0.004	0.004	0.004
Median	0.35	0.34	0.34
Mode	0.37	0.35	0.36
Standard Deviation	0.11	0.11	0.11
Sample Variance	0.013	0.011	0.012
Kurtosis	3.58	3.90	3.77
Skewness	1.60	1.64	1.63
Range	0.80	0.77	0.79
Minimum	0.17	0.16	0.17
Maximum	0.97	0.94	0.95
Confidence Interval (95%)	0.01	0.01	0.01

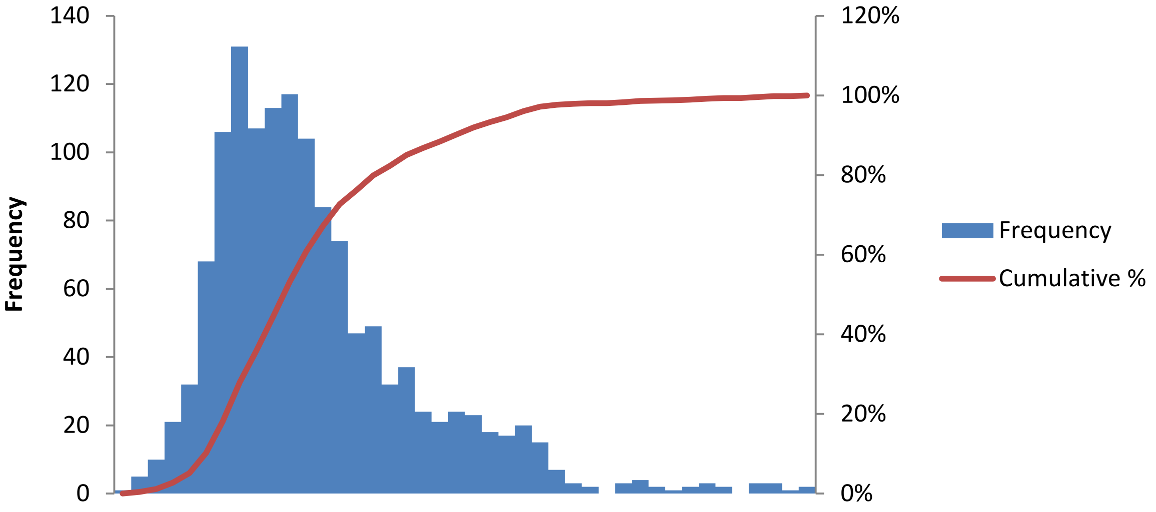

Figure 19. Histogram of wheat emission values for anhydrous ammonia

Table 19. Summary statistics for results for each potential fertilizer type on wheat farms. Results in t CO_2-e/acre

	Anhydrous Ammonia	Urea and Urine	Urea- Ammonium Nitrate
Mean	0.34	0.33	0.33
Standard Error	0.003	0.003	0.003
Median	0.31	0.30	0.31
Mode	0.29	0.28	0.29
Standard Deviation	0.12	0.12	0.12
Sample Variance	0.015	0.014	0.014
Kurtosis	3.03	3.08	3.06
Skewness	1.48	1.49	1.48
Range	0.81	0.77	0.79
Minimum	0.12	0.12	0.12
Maximum	0.93	0.89	0.90
Confidence Interval (95%)	0.01	0.01	0.01

6.0 REFERENCES

Bouwman, A.F., Bouwman, L.J.M. and Batjes, N.H. 2002. Emissions of N2O and NO from fertilized fields: Summary of available measurement data. Global Biogeochemical Cycles 16: 6-1 – 6-13.

EPA. 2010. Inventory of U.S. Greenhouse gas emissions and sinks: 1990-2008. U.S. EPA# 430-R-10-006

Funderburg, E.. 2001. “What Does Organic Matter Do In Soil?”. Available online at http://www.noble.org/ag/soils/OrganicMatter/Index.htm accessed 01-11-2010.

Jaynes, D.B. and D.E. James. 2007. “The Extent of Farm Drainage in the United States”. USDA-ARS-NSTL, Ames, IA. Available online at http://www.ars.usda.gov/SP2UserFiles/Place/36251500/TheExtentofFarmDrainageintheUnitedStates.pdf accessed 03-11-2010.

Killpack, Scott C., Daryl Buchholz. “Nitrogen in the Environment: Ammonia Volatilization” Available online at http://extension.missouri.edu/publications/DisplayPub.aspx?P=WQ257 accessed 03-08-2010.

Pearson and Brown. 2010. Assessment of potential for development of a simplified methodology for accounting for reduction in N2O emissions from change in fertilizer usage. Report to Packard Foundation under #2008-32689.

USDA Natural Resources Conservation Service. “SSURGO Metadata – Table Column Descriptions”. SSURGO Metadata Version 2.2.3 page 7.

6.1 Data References

United States Department of Agriculture (USDA), National Agricultural Statistics Service (NASS), Research and Development Division (RDD), Geospatial Information Branch (GIB), Spatial Analysis Research Section (SARS). “USDA, National Agricultural Statistics Service, 2009 Cropland Data Layer”. USDA, NASS Marketing and Information Services Office, Washington, D.C. 2010. Available online at http://www.nass.usda.gov/research/Cropland/SARS1a.htm accessed 09-01-2009.

Global Administrative Areas. Available online at http://www.gadm.org accessed 09-01-2009.

Soil Survey Staff, Natural Resources Conservation Service, United States Department of Agriculture. U.S. General Soil Map (STATSGO2). Available online at http://soildatamart.nrcs.usda.gov accessed 09-01-2009.

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